REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-05-
0428

1. REPORT DATE *(DD-MM-YYYY)* 30-08-2005	2. REPORT TYPE Final Report	3. DATES COVERED *(From - To)* 01 May 2002-30 Apr. 2005
4. TITLE AND SUBTITLE RF Polymer Research		5a. CONTRACT NUMBER
		5b. GRANT NUMBER F49620-02-1-0196
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Leo Kempel Daniel Killips		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Michigan State University 2120 Engineering Bldg. East Lansing, MI 48824-1226		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Michigan State University 301 Administration Building East Lansing, MI 48824		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approve for Public Release: Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Magneto-dielectric materials offer a new design space for radio frequency (RF) passive components such as antennas, circulators, feed networks, radomes, etc. Polymer nanocomposites offer a means to tailor electric and magnetic properties as well as define necessary mechanical and thermal properties. Recent advances in nanocomposite synthesis methods offer the potential for dramatically different electric and magnetic properties as compared to conventional materials. This research project investigated homogenization techniques, measurement techniques, and potential application of RF polymer nanocomposites.

15. SUBJECT TERMS

Magneto-dielectric, radio frequency, polymer nanocomposite, material characterization, homogenization.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*

RF Polymer Research

Final Report

AFOSR Project Agreement: F-496-200-210196

AFOSR Program Manager: Dr. Charles Lee
Project Start Date: 01 May 2002
Project End Date: 30 April 2005

Principal Investigator: Dr. Leo C. Kempel

Michigan State University

2120 Engineering Building

East Lansing, MI 48824-1226

20051005 129

SUMMARY OF ACCOMPLISHMENTS
RF Polymers offers a whole new design space to radio frequency (RF) engineers. More properly known as magneto-dielectric polymer nanocomposites, these materials have non-trivial permeability as well as permittivity. Hence, the transverse electromagnetic mode (TEM) wave impedance is near, or even above, unity. Such material properties offer designers the ability to miniaturize certain common passive RF components, such as antennas, radomes, and transmission lines among others. Additionally, since a polymer matrix is used as the base for the material, flexibility or rigidity can be realized as needed. Low-cost, high volume production methods such as injection molding are possible.

Traditional RF polymers used rather large inclusions (on the order of 40 microns in diameter or so). Since the density of magnetic materials, either metals or oxides, is substantially larger than the base polymer, the inclusions have a tendency to sink in the uncured material unless some special techniques are used for dispersal. Nanometer-sized inclusions can be dispersed rather well throughout the matrix either through treatment with a surfactant or by locking the particles in the interstitial locations of the polymer matrix. Hence, polymer nanocomposites offer the potential for well-dispersed (e.g. homogeneous) material properties. MSU investigated several aspects of RF polymers exclusive of their chemical properties and synthesis methods. A brief discussion of accomplishments follows with citations to published works.

Reduced Material Characterization Method
During this project, MSU collaborated with a number of researchers – both AFOSR and DARPA sponsored – in the characterization of polymer composite materials. Samples were evaluated using MSU's stripline field applicator from 2-18 GHz. Research material synthesis typically yields a small volume of material (on the order of 1 gram in many cases). Traditional material characterization techniques, especially ones over a wide range of frequencies as compared to cavity methods that are essentially single frequency methods, require substantially more material. The most common example is waveguide testing where the cross-section of a waveguide must be filled. For X-band (8-12 GHz) this then necessitates approximately a 30x10x3mm sample. Hence, MSU developed a method for characterizing materials when only a portion of the waveguide cross-section is filled [1-3]. Experiments have shown that the reduction can be on the order of ¼ in volume. Further studies are planned using a new analysis method developed at MSU that will allow optimization of these reduced-size samples.

Material Property Control
Another aspect of understanding RF polymer potential and applications lie in the ability to tune material properties as needed. In traditional RF engineering, the designer makes compromises, typically in performance, based on the available materials. For RF polymers, the material designer has various choices that impact performance – polymer matrix, inclusion(s), volume fractions, fabrication method, etc. The RF designer has an additional design parameter, the construction of the RF polymer from one or more polymer systems. Hence, material properties can be controlled by layering the material in a two (or greater) phase manner. Alternative arrangements include a milk crate topology,

rods, spheroids, cubes, and other three-dimensional meta-inclusions (e.g. inclusions of synthetic RF polymer materials in another polymer). MSU investigated the use of traditional approximate mixing formulae for nanocomposites and found, not unsurprisingly, that they worked well if the volume fraction was low (a few percent) and if the inclusions were spheroid. An example is illustrated in Figure 1.

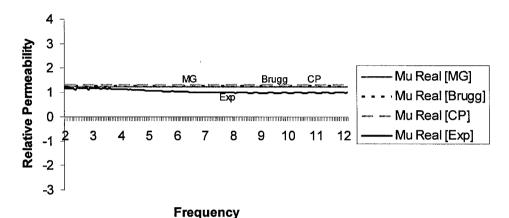## Maxwell Garnett, Bruggeman, Coherent Potential and Experimental Permeability for f=0.1

Figure 1. Comparison of the Maxwell-Garnet, Bruggeman, and Coherent Potential mixing formula vs. experimental data for a volume fraction of 10%.

MSU then began an exact study of layered materials for two reasons: (1) it is a logical step towards the ultimate goal of a three-dimensional (e.g. particle) nanocomposite and (2) the electromagnetics can be solved exactly. Deep sub-wavelength thick alternating material layers were used for this research was the reflection and transmission from each layer was represented by a wave matrix. The cascade of such matrices then represents the stack. Figure 2 illustrates an example where the volume fraction of the two materials is equal.
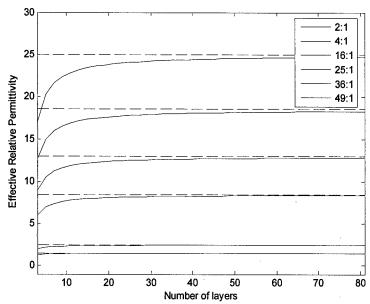
Figure 2. Effective permittivity of an alternating stack with constant total volume as a function of the number of layers and permittivity ratio.

In this, it is seen that a few sub-wavelength layers can be used to tune the homogenized permittivity of the material to a desired value consistent with the permittivity of each of the constituent materials. This work was reported in [4-5].

Material Characterization

MSU characterized materials for a number of AFOSR-sponsored researchers from 1 MHz to 18 GHz. Principally, two test methods were used as screening tools: an Agilent Material Analyzer provided to MSU by AFOSR (1-1000 MHz) and a stripline field applicator (2-18 GHz). MSU also has a number of cavity and waveguide fixtures for smaller bandwidth measurements with greater accuracy. The results of these experiments are left to the material synthesis researchers to report; however, a number of nanocomposite materials showed promise for niche applications.

RF Device Design using RF Polymers

The ultimate impact of RF polymer nanocomposite research is in passive (or active; however, that is the subject of future research) devices. MSU investigated several structures that are common building blocks for passive RF devices. These are: (1) microstrip transmission line, (2) patch antenna, (3) co-planar waveguide, and (4) planar slot antenna. Based on Hansen's approximation for the bandwidth of a patch antenna [6], MSU determined that a TEM impedance greater than free-space will yield a superior bandwidth as shown in Figure 3.
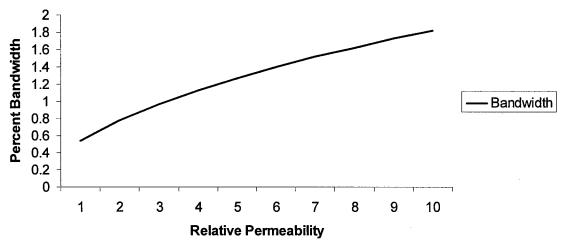
Bandwidth with Constant Permittivity ep=5 at 1 GHz

Figure 3. Patch antenna bandwidth for a relative permittivity of five vs. relative permeability.
Bandwidth is one of the key parameters that determine the utility of an antenna. Air Force applications now routinely use wide bandwidth apertures. In the example above, the bandwidth of the antenna nearly quadrupled compared to the non-magnetic case. Further examples are given in [7]. Note that the material provided (heavily-loaded NiFe composite in a urethane matrix that used large inclusions – ~45 microns) was definitely not low loss and hence the realized bandwidth was due more to loss than permeability.

Design Software
One of the principal initial applications of magneto-dielectric RF nanocomposites is in miniaturization of components. The rationale for using these materials for such a purpose lies in the fact that at a given frequency, the wavelength in the material is smaller than that in air or in a non-magnetic material with identical permittivity. Examples of RF devices for which this is true is the patch antenna where the dimensions of the patch are approximately one half wavelength in the substrate material. However, most devices including the patch exist in a heterogeneous region, e.g. the patch lies in a substrate air interface. Accurate simulation of the electromagnetic fields using most design tools required on the order of forty samples per wavelength. As a result, the aperture from the perspective of the air region is greatly over-sampled compared to the substrate region. This leads to very long solution times that make simulation of complex apertures impractical. MSU developed a hybrid prism-hexahedral design tool that reduces the degrees-of-freedom for geometrically constrained problems compared to conventional prism-only methods. The result is accurate simulations with less effort for apertures (or open microstrip lines, co-planar waveguides, etc.) that utilize RF polymers. This work is discussed in detail in [8-9].

REFERENCES
1. A. Bogle, Electromagnetic Material Characterization using a Partially Filled Rectangular Waveguide, M.S. Thesis, Michigan State University, 2004.
2. A. Bogle, M. Havrilla, L. Kempel, E. Rothwell, and D. Nyquist, "Electromagnetic material characterization using a partially filled rectangular waveguide," *26th AMTA Meeting & Symp.*, Stone Mountain, GA, Oct. 2004.

3. A. Bogle, M. Havrilla, L. Kempel, E. Rothwell, and D. Nyquist, "Use of a partially-filled rectangular waveguide for evaluation permittivity and permeability," *J. Electromagnetic Waves and Appl.,* pp. 1291-1306, 2005.
4. D. Killips, Classical Mixing Approaches to Determine Effective Permittivity and Permeability of a Two-Phase Mixture, M.S. Thesis, Michigan State University, 2004.
5. D. Killips, L. Kempel, and E. Rothwell, "Analysis of layered dielectrics on effective permittivity using wave matrices," *2005 Antennas Propagat. Symp.,* Washington, DC, July 2005.
6. Hansen R.C., and Burke, M., "Antennas with Magneto-Dielectrics", *Microwave and Optical Technology Letters*, **26(2),** 75-78, July 20 2000.
7. M. Scott, *et al.* (Mission Research Corporation), "RF Polymers for Integrated Sensors," Final Report, Contract # DAAH01-02-C-R216, 2005.
8. J. Meese, Mixed Element Formulation for the Finite Element-Boundary Integral Method, Ph.D. Dissertation, Michigan State University, 2003.
9. J.Meese, L. Kempel, and S.W. Schneider, "Mixed element formulation for the finite element-boundary integral method," *ACES Journal, accepted.*

Researchers Supported
1. Dr. Leo C. Kempel: Associate Professor
2. Mr. Jeffery Meese: Graduate student (part-time).
3. Mr. Dan Killips: Graduate student.
4. Mr. Andrew Bogle: Graduate student (part-time).

Published Papers, Reports, and Theses

1. J. Meese, Mixed Element Formulation for the Finite Element-Boundary Integral Method, Ph.D. Dissertation, Michigan State University, 2003.
2. D. Killips, Classical Mixing Approaches to Determine Effective Permittivity and Permeability of a Two-Phase Mixture, M.S. Thesis, Michigan State University, 2004.
3. A. Bogle, Electromagnetic Material Characterization using a Partially Filled Rectangular Waveguide, M.S. Thesis, Michigan State University, 2004.
4. L. Zong, S. Zhou, R. Sun, L.C. Kempel, and M. Hawley, "Dielectric analysis of a crosslinking epoxy resin at a high microwave frequency," J. Polymer Science Part B: Polymer Physics, 42, pp. 2871-2877, 2004.
5. L. Zong, S. Zhou, N. Sgriccia, M. Hawley, and L. C. Kempel, A Review of Microwave-Assisted Polymer Chemistry (MAPC), *J. Microwave*, 38, pp. 49-74, 2003.
6. L. Zong, L.C. Kempel, M. Hawley, "Dielectric Properties of Polymer Materials at a High Microwave Frequency," *2004 IEEE Antennas Propagat. Society Symp.,* Monterey, CA, June 2004.
7. D. Killips, A. Bogle, L. Kempel, E. Rothwell, D. Nyquist, and M. Scott, "Microwave characterization of magnetized RF polymer material properties," *25th AMTA Meeting & Symp.,* Irvine, CA, Oct. 2003.
8. D. Killips, S. Cossmann, and L. Kempel, "Planar passive microwave devices on magneto-dielectric substrates," *26th AMTA Meeting & Symp.,* Stone Mountain, GA, Oct. 2004 .

9. A. Bogle, M. Havrilla, L. Kempel, E. Rothwell, and D. Nyquist, "Electromagnetic material characterization using a partially filled rectangular waveguide," *26th AMTA Meeting & Symp.*, Stone Mountain, GA, Oct. 2004.

10. L. Zong, G. Charvat, L. Kempel, and M. Hawley, "Automated method for characterizing temperature dependent dielectric materials," *26th AMTA Meeting & Symp.*, Stone Mountain, GA, Oct. 2004.

11. A. Bogle, M. Havrilla, L. Kempel, E. Rothwell, and D. Nyquist, "Use of a partially-filled rectangular waveguide for evaluation permittivity and permeability," *J. Electromagnetic Waves and Appl.*, pp. 1291-1306, 2005.

12. J.Meese, L. Kempel, and S.W. Schneider, "Mixed element formulation for the finite element-boundary integral method," *ACES Journal, accepted.*

13. R. Sun, S. Zhou, L. Zong, D. Mandal, L.C. Kempel, M.C. Hawley, and A. Benard, "Coupled Electromagnetic Thermal and Kinetic Modeling for Microwave Processing of Polymers," *the 4th World Congress on Microwave and RF Applications,* November 2004, Austin, TX (**2ⁿᵈ Place in Academic Poster Competition**).

14. L. Zong, S. Zhou, R. Sun, L.C. Kempel, and M.C. Hawley, "Dielectric Properties of Crosslinking Epoxy Resins at 2.45 GHz", *the 4th World Congress on Microwave and RF Applications*, November 2004, Austin, TX.

15. L. Kempel, S. Schneider, J. Radcliffe, D. Janning, and G. Thiele, "FE-BI analysis of a leaky-wave antenna with resistive sheet termination," *21th Review of Progress in Applied Computational Electromagnetics*, Honolulu Hawaii, April 2005.

16. D. Killips, L. Kempel, and E. Rothwell, "Analysis of layered dielectrics on effective permittivity using wave matrices," *2005 Antennas Propagat. Symp.,* Washington, DC, July 2005.

17. P.K. Mercure, R. Haley, A. Bogle, and L. Kempel, "Three-dimensional isotropic meta-materials," *2005 Antennas Propagat. Symp.,* Washington, DC, July 2005.

18. L. Kempel, S. Schneider, T. Kastle, and G. Thiele, "Comparison of two termination schemes for a half-width leaky-wave antenna," *2005 URSI Meeting,* Washington, DC, July 2005.